Deep levels in p-type 4H-SiC induced by low-energy electron irradiation

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Abstract. We have characterized deep levels in as-grown and electron irradiated p-type 4H-SiC epitaxial layers by the current deep-level transient spectroscopy (I-DLTS) method. A part of the samples were irradiated with electrons in order to introduce defects. As a result, electron irradiation on p-type 4H-SiC creates complex defects including carbon vacancy or interstitial. Moreover, the observed deep levels are different before and after annealing, and thus annealing may change the structures of defects.

Introduction

SiC is a promising material for high power and high frequency devices with low-power loss. Among the various SiC polytypes, 4H-SiC is the most promising one for high power device applications because of its high breakdown voltage and high carrier mobility. In addition, high-quality large size wafers are commercially available. However, even in high quality SiC epilayers, microscopic defects, which generate deep levels in the band gap, still exist. Influence of such deep levels on electrical properties will be serious in view of device applications.

In the past, a lot of studies for deep levels in n-type 4H-SiC have been reported, and the results have indicated that carbon vacancies form a deep level behaving as a recombination center [1-3]. We have also found by carrier lifetime observation that defects related to the carbon vacancy in p-type 4H-SiC behave as recombination centers [4,5]. However, deep levels in p-type 4H-SiC have seldom been reported [6], and thus recombination centers in p-type epilayers have not been identified yet. Therefore, evaluation of deep levels in p-type 4H-SiC is important. Deep-levels in semiconductors were generally evaluated by a capacitance deep-level transient spectroscopy (DLTS) method. However, we were not able to perform accurate DLTS measurement for p-type 4H-SiC because of its high resistivity. Therefore, in this work, we performed current-DLTS (I-DLTS) for epitaxial p-type 4H-SiC both with and without carbon vacancies introduced by electron irradiation.

Experiment

The samples were cut from an Al-doped p-type epitaxial layer grown on 8^o-off (0001) Si-face B doped bulk p-type 4H-SiC. Nominal Al doping concentration was 2.0×10^{16} cm^{-3}, and the epilayer thickness was ~10 μm. We cut the epilayer to several pieces. One of the pieces was employed in the as-grown condition (As-grown). The 160 keV electrons were irradiated to other pieces and this electron energy displaces only carbon atoms but not silicon atoms in SiC [1]. The electron doses were either 1.0×10^{16} cm^{-2} (Ele16) or 1.0×10^{17} cm^{-2} (Ele17) [4,5]. The annealing at 1000^oC in N_2 ambient was performed for the samples prepared under the same conditions as As-grown, Ele16 and Ele17, and we name them Annealed, Ele16A and Ele17A, respectively [5]. We formed Schottky and ohmic contacts on the samples, and performed capacitance-voltage (*C-V*) measurements for these samples in order to estimate the net acceptor concentration. *C-V* characterisitics were obtained under the measurement fequency of 1 kHz because we were not able to obtain high-frequency capacitance because of high resistance of the samples. Then, I-DLTS measurements were performed for the samples.

Experimental Results

Figure 1 shows the distribution of net acceptor concentration obtained from *C-V* measurements for all the samples. The acceptors are uniformly distributed within depths from 200 to 500 nm for all the samples. For As-grown, the net acceptor concentration is 3.5-3.9 $\times$ 10^{16} cm^{-3}, and for Ele16, it is 3.3-3.7 $\times$ 10^{16} cm^{-3}. On the other hand, for Ele17, the net acceptor concentration is 2.5-2.9 $\times$ 10^{16} cm^{-3}, which is lower than that in As-grown and Ele16. Therefore, high-density electron irradiation would decrease the net acceptor concentration. In addition, annealing slightly increases net acceptor concentrations except for the sample irradiated with 10^{17} cm^{-2}.

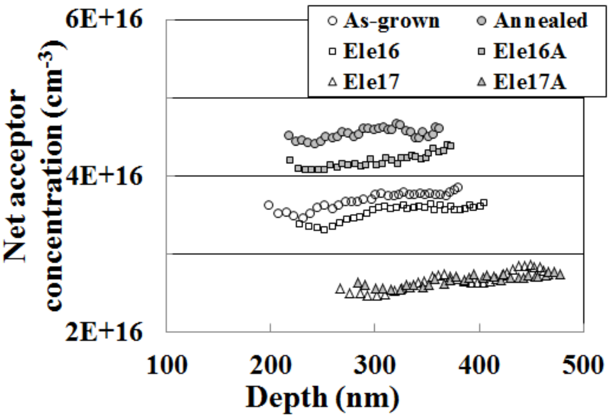

Fig. 1 Distribution of net acceptor concentration for all the samples.

Figure 2 shows the I-DLTS spectra for As-grown, Ele16 and Ele17. For As-grown, three peaks were observed at 112 K (as-1), 150 K (as-2) and 170 K (as-3). We were not able to estimate trap densities, *Nt*, and activation energies, *Ea*, for peaks as-2 and as-3 due to their overlap. For Ele16, peaks were observed at 130 K (e16-1), 150 K (e16-2) and 165 K (e16-3), while for Ele17, peaks were at 145 K (e17-1), 175 K (e17-2) and 205 K (e17-3). *Ea*, *Nt* and peak temperature, *Tmax*, estimated from the Arrhenis plot are listed in Table 1, but parameters for e16-3, e17-2 and e17-3 were not estimated because of their broadness.

Figure 3 shows the I-DLTS spectra for Annealed, Ele16A and Ele17A. For Annealed, peaks were observed at 150 K (annealed-1) and 190 K (annealed-2). For Ele16A, peaks were at 152 K (e16A-1) and 192 K (e16A-2), while for Ele17A, peaks were at 130 K (e17A-1), 146 K (e17A-2) and 170 K (e17A-3). Trap parameters for these peaks are also listed in Table 1 except for e17A-3 which shows broad shape. We consider that, among the observed deep levels, annealed-1 and e16A-1 originate from the same defects, and also annealed-2 and e16A-2 from the same defects because of similarity of their parameters.

Figures 4 and 5 show influence of the reverse bias in DLTS measurements on the Arrhenis plot for the observed peaks in the samples without and with annealing, respectively. Injection biases were 0 V for all the measurements, and we can calculate the electric field applied to the trap from the injection and reverse biases. When the traps are acceptor-type in p-type semiconductors, change in *Ea* is proportional to square root of the electric filed (the Poole-Frenkel effect) [7]. As shown in Figures 4 and 5, the peak temperatures of e17-1, e17A-1 and e17A-2 seem to depend on the electric field, but since *Ea* values (slope of the Arrhenius plot) for these peaks do not depend on the electric field, all the observed deep levels would originate from donor-type defects.

Discussion

After electron irradiation, the peaks different from those observed in As-grown were created (e16-1, e16-2, e17-1 and e17-3). If those peaks originated from a simple carbon vacancy, their peak height should increase monotonically with the dose of the electron beam. However, their height did not

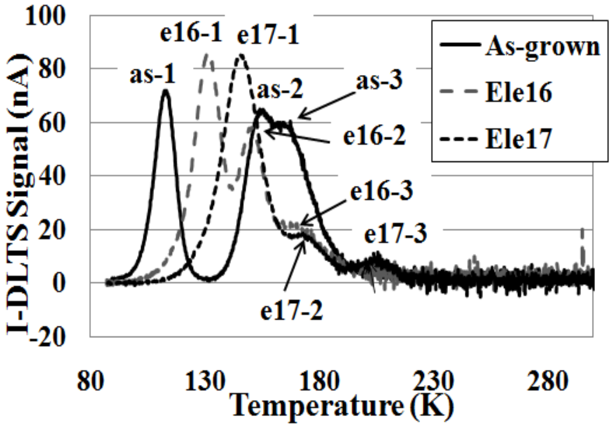

Fig. 2 I-DLTS spectra for the samples without annealing (τ =1.8 ms).

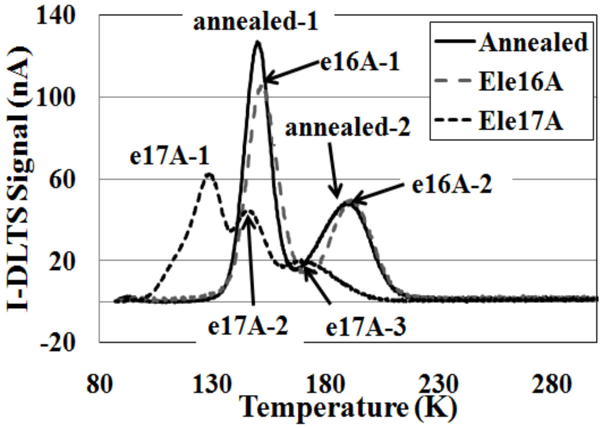

Fig. 3 I-DLTS spectra for the samples with annealing (τ =1.8 ms).

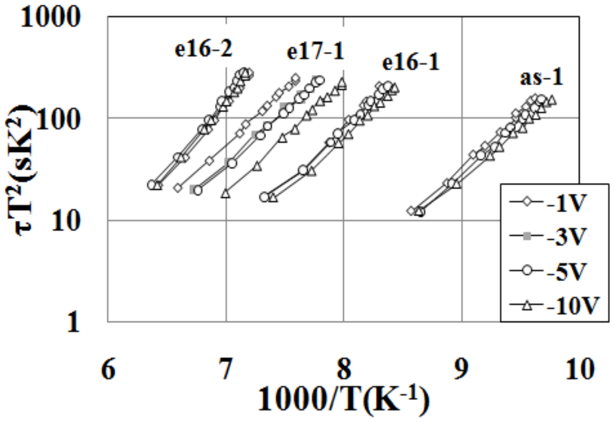

Fig. 4 Arrhenis plots obtained with several reverse biases for the peaks observed in the samples without annealing.

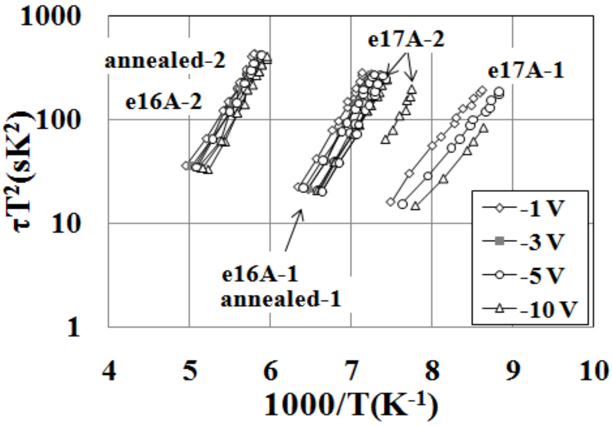

Fig. 5 Arrhenis plots obtained with several reverse biases for the peaks observed in the samples with annealing.

Table 1. Trap-parameters estimated from the peaks.

Sample	Label	*Tmax* (K)	*Nt* (cm^{-3})	*Ea* (eV)
As-grown	as-1	112	1.6×10^{17}	0.21
Ele16	e16-1	130	2.4×10^{17}	0.22
	e16-2	150	1.4×10^{17}	0.29
Ele17	e17-1	145	2.0×10^{17}	0.21
Annealed	annealed-1	150	4.0×10^{17}	0.28
	annealed-2	190	1.4×10^{17}	0.27
Ele16A	e16A-1	152	3.4×10^{17}	0.27
	e16A-2	192	1.6×10^{17}	0.25
Ele17A	e17A-1	130	1.7×10^{17}	0.19
	e17A-2	146	9.8×10^{16}	0.29

increase with the dose of the electron beam. Therefore, the observed peaks are not due to a simple carbon vacancy but due to complex defects including carbon vacancy or interstitial. The carrier lifetime became short after the electron irradiation [4,5], and therefore these complex defects behave as recombination centers.

We next discuss effects of annealing. For the samples without irradiation, we expected that the defects structure hardly changed by annealing at 1000 °C because this temperature was lower than the epitaxial growth temperature. However, DLTS spectra changed and the carrier lifetimes shorten after annealing [5]. Therefore, even 1000 ^{o}C annealing may introduce reconstruction of defects inducing carrier lifetime killers. For the samples with 10^{16} cm^{2} irradiation, defects with similar parameters (e16-2 and e16A-1) were observed both before and after annealing. *Nt* of these peaks increased after annealing, but the carrier lifetime increased after annealing [5]. Therefore, we can conclude that these peaks do not behave as recombination center. For the samples with 10^{17} cm^{2} irradiation, observed deep levels are different between with and without annealing. The carrier lifetime increased after annealing [5], and it is difficult to identify the deep-levels corresponding to the dominant recombination centers in the samples with 10^{17} cm^{2} irradiation.

We compare the present results with a previous report for p-type 4H-SiC [6]. Danno et al. reported DLTS results for a p-type epilayer with acceptor concentration of 6.5×10^{15}-2.8×10^{17}cm^{-3}. Our as-grown sample shows the peaks at 112 K (as-1), 150 K (as-2) and 170 K (as-3), while they observed the peak at 240K. Therefore, observed peaks are completely different between their and our as-grown samples. A noticeable difference between their and our samples is acceptor concentration, and thus deep levels in p-type 4H-SiC introduced during epitaxial growth may depend on doping concentration. They also observed deep levels in samples annealed at 1200 ^{o}C or electron irradiated. Their annealing and electron irradiation conditions are similar to ours, and they observed deep levels different from those observed in this study. Because, as noted above, deep levels in as-grown epilayers would depend on the acceptor concentration, deep levels created by annealing and electron irradiation should also depend on the acceptor concentration.

Summary

In this work, we have characterized deep levels in as-grown and electron irradiated p-type 4H-SiC epitaxial layers by the I-DLTS method. We did not observe deep levels originating from a simple carbon vacancy, but we observed deep levels from complex defects which include carbon vacancy or interstitial induced by the electron irradiation. In addition, 1000^{o}C annealing may reconstruct defects in the as-grown and electron irradiated samples.

Acknowledgements

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